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THE EFFECT OF HUMIDITY ON THE STABILITY OF LTCC PRESSURE SENSORS

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Abstract

LTCC-based pressure sensors are promising candidates for wet-wet applications in which the effect of the surrounding media on the sensor's characteristics is of key importance. The effect of humidity on the sensor's stability can be a problem, particularly in the case of capacitive sensors. A differential mode of operation can be a good solution, but manufacturing the appropriate sensing capacitors remains a major challenge. In the case of piezoresistive sensors the influence of humidity is less critical, but it still should be considered as an important parameter when designing sensors for low-pressure ranges. In this paper we discuss the stability of the sensors' offset characteristics, which was inspected closely using experimental and numerical analyses.

Keywords: Thick-film piezoresistive sensors, capacitive pressure sensors, offset stability, relative humidity.

1. Introduction

Recently, the research field of ceramic micro-systems realized using LTCC (Low-Temperature Co-fired Ceramic) materials and technology has made considerable progress. LTCC-based micro-systems consisting of complex three-dimensional (3D) structures with channels and cavities can also incorporate different functional thick-film elements, sensors and actuators. Among the most frequently investigated are pressure/force sensors [1-3]. This is because LTCC technology combines many of the advantageous features for pressure sensors: the ease of 3D structuring, the availability of relatively thin sheets and compatible functional thick-film materials and a relatively low Young's modulus (substantially lower than that of Al_2O_3) with a still reasonable mechanical strength. A large number of ceramic green tapes can be laminated and fired together to form a rigid substrate with high-density interconnections, together with functional 3D structures that have diaphragms, cavities and channels. The laminated structures are co-fired at relatively low temperatures (850–900°C) in comparison with the sintering temperature for Al_2O_3 (typically 1300°C). This allows manufacturing of the whole sensor structure together with the sensing elements and interconnections in a one-step process [4, 5].

Ceramic pressure sensors (CPS) are normally used in special applications, mainly in harsh environments. From this point of view, LTCC-based pressure sensors can also be considered as promising candidates for wet-wet applications. For such applications the effect of the surrounding media on the sensor's characteristics is of key importance and should be investigated carefully. One of the most common and in many cases critical media is humid air, with a high relative humidity (RH) above 60%. The effect of the humidity of the surrounding atmosphere on the stability of ceramic pressure sensors can be a problem, particularly in the case of capacitive pressure sensors. In order to reduce the undesired effects

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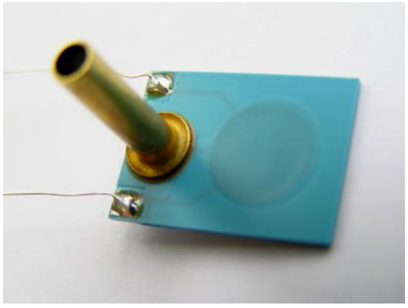
on the capacitive sensing structure a differential mode of operation can be a good solution. However, manufacturing ceramic structures with the appropriate pairs of capacitive sensing elements remains a major challenge. In the case of thick-film piezoresistive pressure sensors the influence of humidity is less critical, but it should still be considered as an important parameter when designing the sensors for very precise measurements in low-pressure ranges. One of the sensor parameters that is most affected by humidity is the offset voltage. For most applications it is typically required for the offset stability to be within 0.1% of full scale per year. Therefore, the effect of humidity can be critical, particularly for low-pressure sensors.

In this paper we present some results of our investigation of the effect of a humid atmosphere and moisture on the properties of LTCC-based capacitive and piezoresistive pressure-sensing elements. The discussion is concentrated on the influence of the humidity on the stability of the sensors' offset characteristics, which was inspected closely through experimental and numerical analyses of various situations.

2. Capacitive ceramic pressure sensor

A schematic representation of the sensor structure and the prototype of the capacitive CPS built-up in an LTCC structure with cofired thick-film electrodes inside the cavity is presented in Fig. 1. Typical sensor characteristics were discussed in [6-8]. Furthermore, it was presented in [9] that the effect of humidity on the sensor characteristics can be a problem, even for the differential mode of operation and an optimised design of the electrodes. In addition to the experimental study we performed some numerical analyses that helped in a further study of the effect [10, 11].

a) 

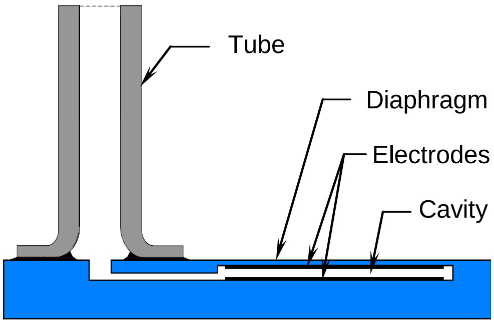
b) 

Fig. 1. Capacitive CPS in LTCC structure: a) the prototype and b) the schematic representation of the cross-section (not to scale).

A finite-element analysis (FEA) of the specific physical situation in the capacitive LTCC structure in a humid atmosphere and in the different media helped in clarifying the experimentally obtained results. The numerical model was built in the FlexPDE finite-element (FE) code. The capacitance of the sensor was calculated from the energy accumulated within the ceramic body and the surrounding media as in [12]. First, the changes in the capacitance of the unloaded sensor (C_0) were observed for the sensor at a constant temperature and different humidities. The relative dielectric constants (ε_r) used in the model are as follows: 7.8 for LTCC, 80 for the water and the ε_r of the humid air was calculated from an empirical relation, as in [13]. In this way for the normal atmospheric pressure of 101325 Pa, and an ambient temperature of 25°C, ε_{r_air} values of 1.00064 and 1.00078 were obtained for 30% and 90% RH, respectively. Due to the considerable discrepancy between the numerical and experimental results obtained for the idealised model of the physical situation at a high relative humidity of the surrounding air (the FEA revealed much smaller changes in C_0 than were measured), this was followed with an analysis of the sensors in direct contact with the

Metrol. Meas. Syst., Vol. XIX (2012), No. 1, pp. 133-140.

water. In [12] the FEA was carried out for the capacitive ceramic sensor in a humid atmosphere under the assumption that in the case of a high RH of the surrounding atmosphere the surface of the ceramic can be covered with a thin film of condensed water. Alternatively, the model in which a thin layer of the ceramic on this surface (with a roughness Ra < 0.45 μm) can have considerably increased permittivity due to the effect of humidity was used. Due to lack of accurate experimental data for the dielectric properties of the ceramic for such situations we were aware of the inexactness of such assumptions and used the FEA only to predict the trends.

Using the same assumption in the model of the ceramic CPS for this case study, and introducing for the case of 80% RH a 5-μm-thick layer of condensed water on the ceramic surface, we obtained relatively good agreement with the measured capacitance C_0. The results of both the numerical analysis and the measurements are presented in the same graph by using different x axes (Fig. 2). A comparison of these numerical and experimental results showed that the changes in C_0 when the sensor is put in a very humid atmosphere are mainly due to the effect of the humidity on the external surface of the ceramic body. For a RH > 80% this effect prevails over the effect of the changed dielectric properties of the air and the increased losses between the sensor electrodes and obviously this can noticeably influence the sensor characteristics.

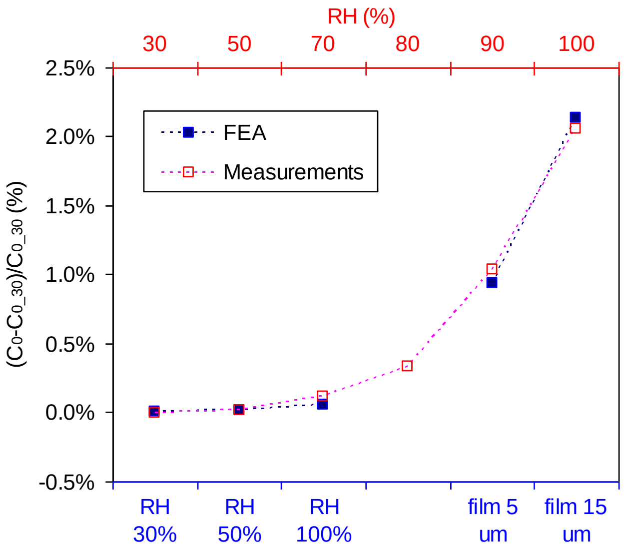


Fig. 2. Measured and simulated changes in C_0 for different situations. (The bottom X-axis is for FEA assumptions and the top X-axis is for the measurement results).

3. Piezoresistive ceramic pressure sensor

The piezoresistive LTCC-based CPSs treated in this case study were implemented in the popular four-element, Wheatstone-bridge configuration. The prototypes (Fig. 3) were made using the Du Pont 951 tapes and 2041 thick-film resistor material. The typical sensor characteristics were already discussed in [14, 15].

The offset stability test revealed an observable influence of the RH of the atmosphere. The results obtained for the series of sensors with the diaphragms with different thicknesses (100 μm, 250 μm and 400 μm) and of the same diameter (6.8 mm) are presented in Fig. 4. The sensors were measured continuously with a sampling rate of 0.03 Hz under controlled conditions: the temperature of 25°C and 30% RH for the first 48 hours followed by 50% RH. In the dry atmosphere all the sensors showed very good stability. The maximum changes in the offset voltages were less than ±10 μV at a supply voltage of 5V. The increase of the RH to 50% had an observable effect on the stability of some samples. The most significant changes in the offset voltages resulting from changing the RH (of about 40 μV) were measured for sensors with the thinnest diaphragm.

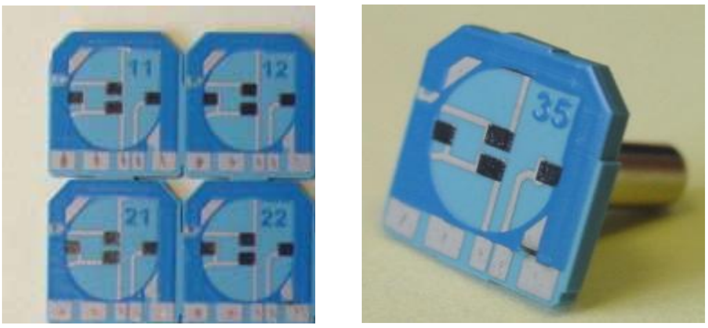


Fig. 3. Prototypes of the LTCC-based piezoresistive CPS.

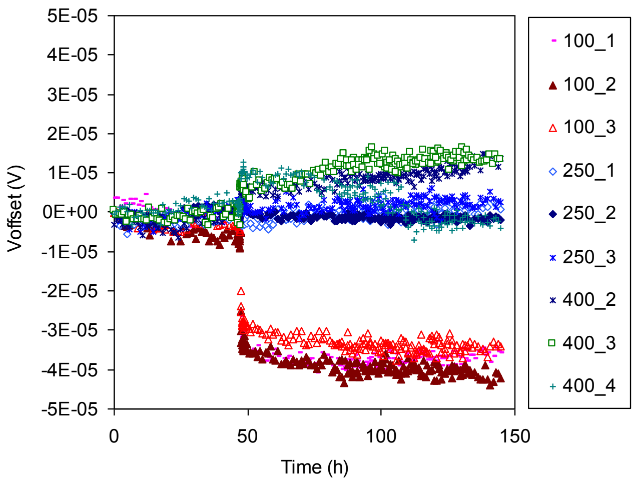
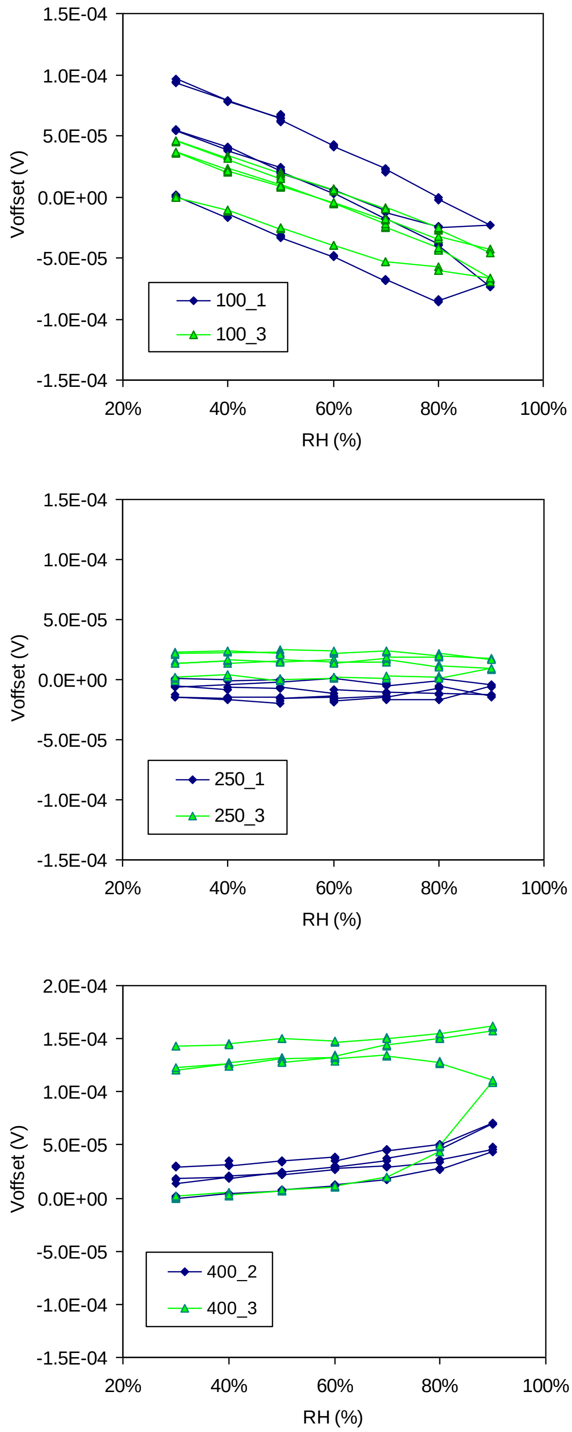


Fig. 4. The offset voltage (Voffset) of the piezoresistive CPS (samples 100_x, 250_x and 400_x, with 100-μm, 250-μm and 400-μm diaphragms respectively) measured at 25°C and 30% RH (for the first 48 hours) and then at 50% RH (for further 160 hours).

In order to inspect closely this effect and analyze the offset stability in terms of RH, the offset voltage was further measured during two RH-cycles (at 25°C and the RH range from 30-90% with a step of 10% and with a 2-hours stabilisation at each step). The results obtained for the sensors with 100-μm and 250-μm diaphragms are presented in Fig. 5. In the graphs only the changes in the offset voltage are presented. The initial values are set to zero, so that tracking the curves starting from the zero point (Voffset = 0) can give information on the measurements' order and the hysteresis. Again, the measurements showed a noticeably larger effect of the humidity on the offset of the sensors with 100-μm diaphragms. In this particular case the offset versus RH characteristics have a negative slope and exhibit a relatively high hysteresis. However, since a similar hysteresis was observed for the sensors with a 400-μm diaphragm we could not assert that the thickness of the diaphragm is the only, or even the main, reason for the emphasized effect. In the next steps all the sensors were further passed through additional RH-cycles and measured. The characteristics obtained were almost the same as in Fig. 5, only that the hysteresis of the characteristics representing the RH

Metrol. Meas. Syst., Vol. XIX (2012), No. 1, pp. 133-140.

dependence of the sensors with a 400-µm diaphragm was smaller (Fig. 6). Such results indicated that there could be some influence of the humidity on the experimental set-up.



a) b) c)

Fig. 5. Offset voltage versus relative humidity for: a) the sensors with 100-µm diaphragm (samples 100_1 and 100_2), b) the sensors with 250-µm diaphragm (samples 250_1 and 250_3) and c) the sensors with 400-µm diaphragm (samples 400_2 and 400_3).

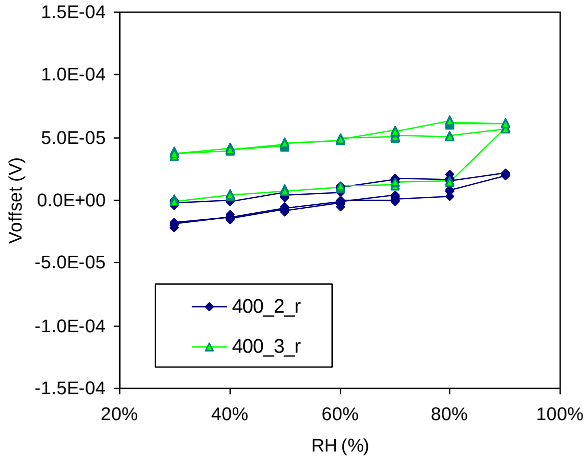


Fig. 6. Offset voltage versus relative humidity for the sensors with 400-μm diaphragm after two additional RH cycles.

In order to assess the effect of the humid atmosphere on the wires and connectors in the experimental set-up that are placed in the chamber during the measurements and so also exposed to the humid atmosphere together with the sensors, additional measurements were performed as follows. The idea was to keep the sensors at a constant dry atmosphere and repeat the RH cycling procedure. This was realized by measuring the sensors closed in plastic tubes with dry atmosphere (RH of 30%) inside. In order to use the same experimental set-up for the measurements even in this case, about 5 cm long wires with an additional connector were inserted between the wires and the sensor pins. The results obtained are presented in Fig. 7. It is evident that the changes in the offset voltages of the sensors that were closed in the plastic tubes with low RH can be for RH in the chamber > 80% even higher than the changes in the offset voltage in the case presented in Fig. 4. This indicated that the influence of the humid atmosphere on the electrical connections in the experimental set-up can prevail over the information about the offset stability of the sensor. In order to visualize the effect of the humidity in both situations, i.e., the sensor in the humid atmosphere and the sensor in a plastic tube, the measurements of the sensors with 100-μm diaphragms are collected in a common graph (Fig. 8).

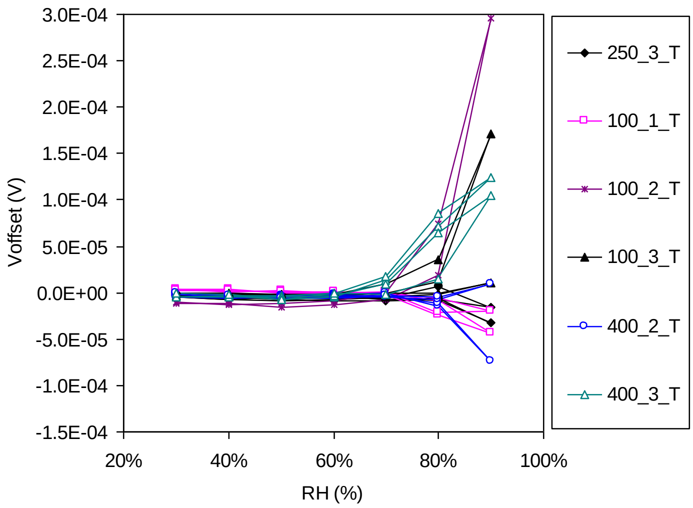


Fig. 7. Offset voltage versus relative humidity for the sensors closed in the plastic tubes with about 30% RH and the connectors exposed to different RH.

Metrol. Meas. Syst., Vol. XIX (2012), No. 1, pp. 133-140.

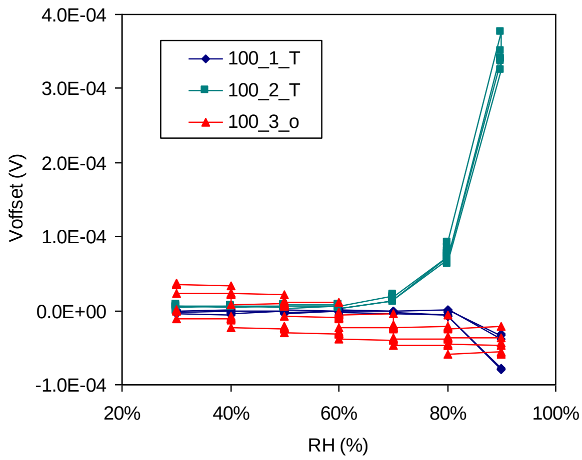


Fig. 8. Offset voltage versus relative humidity for the sensors with 100-µm diaphragm; two sensors are closed in the plastic tubes with about 30% RH (label T) and one sensor is in a humid atmosphere (label o).

The graph in Fig. 8 shows the offset voltage of three sensors with 100-µm diaphragms; two of them closed in the plastic tubes in a dry atmosphere and one subjected to the RH cycles. These results indicate that the effect of the humid atmosphere on the connectors and connection wires to the measurement equipment, which are also subjected to the humid atmosphere during the tests, may strongly influence the measurement results. This effect of the humid atmosphere can be even higher than the effect of the humid atmosphere on the thick-film sensing resistors, particularly for RH > 80%. Appropriate control and elimination of this effect should be considered as part of the sensor-package design.

4. Conclusions

Experimental and numerical analyses of the effect of humid atmosphere on the stability of the capacitive CPS showed that the characteristics can be strongly affected by the parasitic capacitances resulting from the humid atmosphere and particularly the condensed water on the outer walls of the sensor. The effect of changing the dielectric properties of the ceramic on its surface (roughness Ra < 0.45 µm) in direct contact with the humid atmosphere still remain a critical problem which should be considered for each specific application separately.

In the case of piezoresistive pressure sensors the influence of humidity is less critical, but it should still be considered as an important parameter when designing the sensors for very precise measurements in low-pressure ranges. In our future work the appropriate protection of the sensors' surface and appropriate designs avoiding direct contact of the functional films and connections for specific wet-wet applications will be studied.

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